Numerical Modeling of Plasmas Using the TurboWAVE Framework

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Introduction: The turboWAVE framework is a set of software modules used for simulating a wide range of phenomena involving plasmas. Plasma physics arises in several research areas of interest to the Navy, including ultra-intense laser propagation in air, guided electrical discharges, and advanced accelerators. The approach used to model a plasma can differ greatly from one problem to the next because of the variety of scales, geometries, and physical processes that are important in each case. For example, particle models are useful for accelerators, while fluid models are useful for discharges. In virtually all cases, the need for high performance computing eventually arises. The turbo-WAVE framework is designed to simulate a variety of physical systems using the massively parallel architectures that are likely to be available in the near term, including those currently provided by the Department of Defense High Performance Computing and Modernization Program (DoD-HPCMP).

Framework Description: One of the key elements of the turboWAVE framework is the facility for parallel processing. This facility is built on a set of C++ classes which support domain decomposition with respect to fields and particles. The framework also provides classes that are useful for extracting information from large datasets, and writing out diagnostic files in a parallel environment. The framework provides a variety of numerical algorithms, such as electromagnetic field solvers, rapid elliptical solvers, fluid advection routines, particle pushers, and others. These are all designed to work in any number of dimensions, and in some cases are able to function in multiple coordinate systems.

Advanced Accelerators: The turboWAVE modules that implement the particle-in-cell (PIC) technique are designed to model advanced accelerator concepts such as the Laser Wakefield Accelerator (LWFA). The LWFA uses an ultra-intense laser pulse to drive a plasma wave, which can be used to accelerate electrons. Due to the extreme electric fields produced in the plasma wave (GV/cm), the length of the accelerator can be orders of magnitude shorter than a conventional accelerator of the same energy scale. TurboWAVE models such accelerators using a fully electromagnetic field solver coupled to a fully relativistic particle pusher. It includes an optional optimization called the ponderomotive guiding center algorithm,[1] which averages over optical periods. Figure 6 shows data from a turboWAVE simulation in which a 2-TW, 50-fs laser pulse is focused into a plasma with an electron density of about 10^{18} cm^{-3}. The data is a volumetric rendering of the scalar potential associated with the relativistic plasma wave driven by the laser radiation. Structures of this type, which are in motion at nearly the speed of light, can trap and accelerate electrons from either the background plasma or an external source. The accelerated spectra observed in turboWAVE have been shown to agree with those observed in experiments at NRL.[2,3]

Laser Guided Discharges: The turboWAVE modules that solve the hydrodynamic equations for a multi-species plasma are collectively called SPARC (Streamer Propagation and ARCing). These modules are designed primarily for modeling laser guided discharges and laser heated air plasmas. A laser guided discharge uses the plasma filament formed in ambient air by a femtosecond laser pulse as a conducting path which guides an electrical discharge in a chosen direction. Simulating this phenomenon involves electrostatics, air chemistry, and hydrodynamics. The space and time scales involved span orders of magnitude, so specialized algorithms, such as an adaptive grid, are needed to make the simulations practical. A SPARC simulation of streamer propagation is shown in Fig. 7. A streamer consists of an elongated body of plasma immersed in an electric field. The field at the tip of the streamer is larger than the ambient field due to field enhancement. This enhanced field causes avalanche ionization which further elongates the streamer. In Fig. 8, the time evolution of a laser heated air plasma is shown. Initially, the electron density drops due to recombination and attachment. Later in time, as the electron and vibrational temperature increase, the electron density increases. Later still, molecules begin to dissociate.

Summary: The turboWAVE framework is a flexible foundation on which a diverse set of numerical codes can be built. Two codes that have been deployed successfully at NRL are the turboWAVE particle-in-cell code for modeling advanced accelerators, and the SPARC hydrodynamics code for modeling laser guided discharges and laser heated air plasmas

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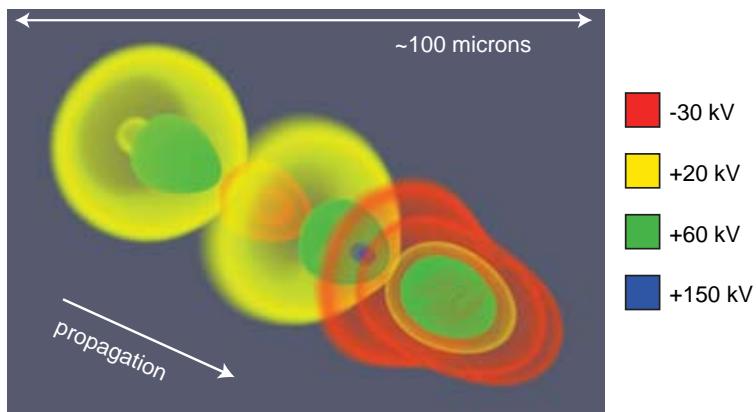
FIGURE 6

The scalar potential in a laser wakefield accelerator as computed by turboWAVE. The structure is in motion at the speed of light. The high potential gradients lead to the rapid acceleration of electrons to high energies.
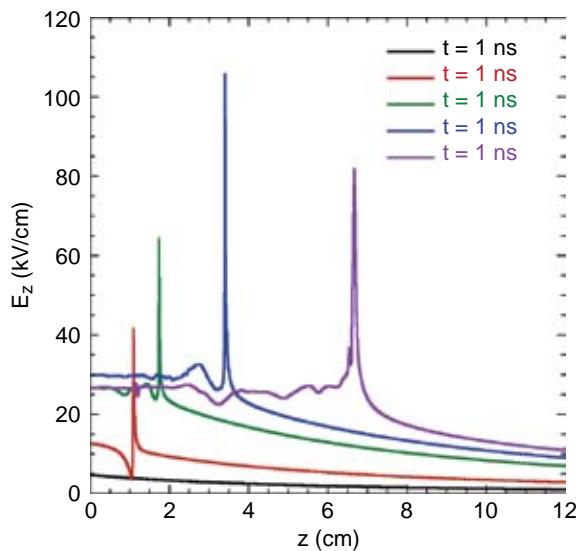
FIGURE 7

Axial electric field associated with a positive streamer driven by a linearly ramped voltage. The electrode is on the left, and the streamer propagates to the right. The large spikes are due to field enhancement at the streamer tip.
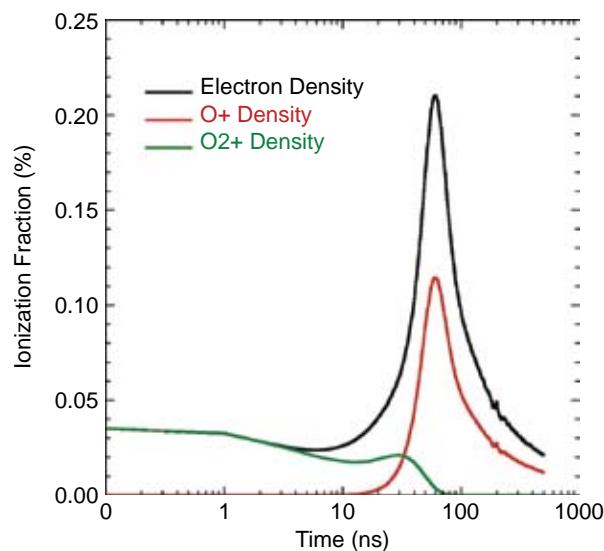
FIGURE 8

Enhancement of an air plasma by a 50-ns, 1-Joule laser pulse. As the air is heated, avalanche ionization overcomes the losses, and the electron density increases. Molecular dissociation can also be seen.